DEVELOPMENT OF A BUFFER GAS-FREE BUNCHER FOR LOW ENERGY RI ION BEAM

M. Togasaki, K. Kurita, K. Yamada, Rikkyo University, Tokyo, Japan
R. Toba, Nagaoka University of Technology, Nagaoka, Niigata, Japan
M. Hara, T. Ohnishi, and M. Wakasugi, RIKEN Nishina Center, Wako, Japan

Abstract

A new-type buncher which is buffer gas-free and workable under the ultra-high vacuum for low energy RI ion beams based on a linear RFQ ion trap was developed. Our idea is to make active use of the fringing fields in a region close to the entrance or the exit of the RFQ to decelerate and stack ions continuously injected into the buncher. As a result of performance experiments, ion beams extracted from the buncher with pulse width of about 500 µs and a stacking efficiency of $^{133}Cs^+$ of 10 % were obtained for the operating frequency of 10Hz. It is usable for bunching ion beams provided from the ERIS (Electron-beam-driven RI separator for SCRIT) in the SCRIT (Self-Confining RI Ion Target) electron scattering facility at RIKEN RI Beam Factory.

INTRODUCTION

The SCRIT (Self-Confining RI Ion Target) is an internal target formation technique for electron scattering off short lived unstable nuclei [1–3]. In the SCRIT electron scattering facility at RIKEN RI Beam Factory [4], we constructed an ISOL-type RI beam generator named ERIS (Electron-beam-driven RI separator for SCRIT) [5]. the ERIS supplys continuous RI ion beam with the energy of 50 keV at maximum. In order to efficiently inject the RI beam from the ERIS into the SCRIT device equipped in an electron storage ring and to produce a sufficiently high luminosity for SCRIT experiment, it is absolutely necessary to bunch the beam with a pulse width of about 500 µs without deteriorating of a vacuum level of less than 10^{-7} Pa.

Therefore, we developed a new-type buncher system for the RI ion beam based on a technique of a linear radiofrequency quadrupole (RFQ) ion trap such as in reference [6] but without using buffer gas and working under the ultra-high vacuum. Our idea is to make active use of the fringing fields in a region close to the entrance or the exit of the RFQ. In this paper, we report results of a verification of the new technique using numerical simulations, and of performance experiments of the buncher system.

PRINCIPLE OF THE BUFFER GAS-FREE BUNCHER

Fringing fields of a linear RFQ

an ideal electrostatic potential generated by rods of a linear RFQ [7] lying along the z-axis with a bore radius r_0, $\phi(x, y, t)$, is given by

$$\phi(x, y, t) = V_{\mathrm{DC}} + \frac{x^2 - y^2}{r_0^2} V_{\mathrm{RF}} \cos \omega t \qquad (1)$$

where V_{RF} and ω are amplitude and angular frequency of an RF voltage respectively, and V_{DC} is an adittional DC voltage applied to the rods. In a region close to end-cap electrodes (hereafter called "barrier" electrodes), however, fringing fields [8–10] are not negligible. The potential $F(x, y, z, t)$ in this region is expressed approximately by

$$F(x, y, z, t) = f(z)\phi(x, y, t) \qquad (2)$$

$$f(z) = 1 - \exp[-az - bz^2] \qquad (3)$$

where a and b are coefficients dependent on the ratio of a distance from the rods to the barrier electrode to r_0, and $z = 0$ corresponds to the position of the barrier electrode [9, 10].

According to the above equations, ions in this region are longitudinally accelerated or decelerated by the RF fringing fields. If energys of the decelerated ions come to be lower than the DC voltage applied to the barrier electrode, the ions should be stacked in the longitudinal barrier-potential well and a bunch beam can be produced by extracting the stacked ions within a short time.

Ion stacking by the fringing fields

We verified the ion stacking phenomenon by the fringing fields using Monte Carlo particle simulations. Numerical solutions of the three-dimensional Laplace equation were employed as models of the fringing fields. Where DC voltage applied to the barrier electrodes is $V_{\mathrm{Barr}} = V_{\mathrm{Acc}} - 0.70$ V, as an example, Figure 1 shows the time evolution of averaged survival rate $\langle S \rangle_{\mathrm{RF}}(t)$ of $^{133}Cs^+$ ions injected into the RFQ within one RF cycle T_{RF} from $t = 0$ for some different values of V_{DC}. $V_{\mathrm{Acc}} = 6.0$ kV is accelerating voltage of ions, and amplitude and frequency of the RF voltage are $V_{\mathrm{RF}} = 300$ V and $\omega/2\pi = 1.6$ MHz respectively.

Total number of stacked ions $N(t)$ in RFQ with continuous beam-injection time t is expressed by

$$N(t) = \frac{I_{\mathrm{inj}} T_{\mathrm{RF}}}{e} \sum_{i=0}^{n} \langle S \rangle_{\mathrm{RF}}(t - iT_{\mathrm{RF}}) \qquad (4)$$

where I_{inj} is the injected beam current, time t is multiple of the RF cycle T_{RF} and

$$n = \frac{t}{T_{\mathrm{RF}}} \qquad (5)$$

Therefore, ion stacking efficiency $\epsilon(t)$ defined as the ratio of the $N(t)$ and total number of injected ions $I_{\mathrm{inj}} t/e$ can be written as

$$\epsilon(t) = \frac{T_{\mathrm{RF}}}{t} \sum_{i=0}^{n} \langle S \rangle_{\mathrm{RF}}(t - iT_{\mathrm{RF}}) \qquad (6)$$

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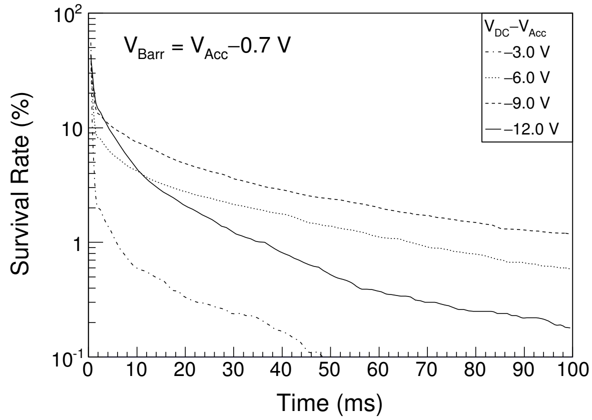

Figure 1: Averaged survival rate $\langle S\rangle_{\mathrm{RF}}(t)$ of $^{133}\mathrm{Cs}^{+}$. Accelerating voltage of the ions is $V_{\mathrm{Acc}} = 6.0\,\mathrm{kV}$, DC voltage applied to the barrier electrodes is $V_{\mathrm{Barr}} = V_{\mathrm{Acc}} - 0.70\,\mathrm{V}$, and amplitude and frequency of the RF voltage are $V_{\mathrm{RF}} = 300\,\mathrm{V}$ and $\omega/2\pi = 1.6\,\mathrm{MHz}$ respectively.

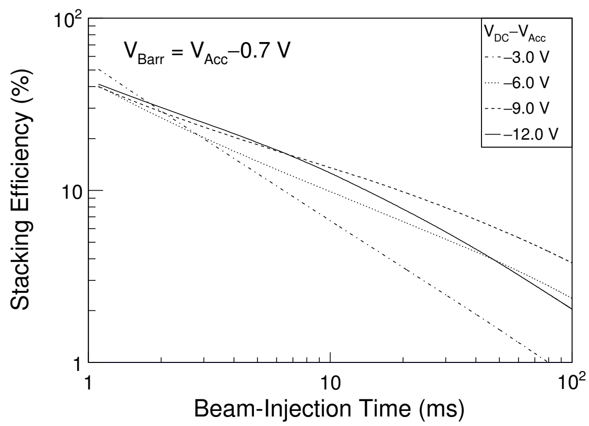

Figure 2: Ion stacking efficiency $\epsilon(t)$ of $^{133}\mathrm{Cs}^{+}$ where t is the beam injection time. V_{Acc}, V_{Barr}, V_{RF}, ω and V_{DC} have same values as in Figure 1.

The $\epsilon(t)$ numerically-calculated from the $\langle S\rangle_{\mathrm{RF}}(t)$ in Figure 1 are shown in Figure 2. Moreover, Figure 3 shows the $\epsilon(t)$ of $^{133}\mathrm{Cs}^{+}$ plotted versus $V_{\mathrm{DC}} - V_{\mathrm{Acc}}$ for $t = 100\,\mathrm{ms}$, and for some different values of V_{Barr}.

EXPERIMENTAL SETUP

Figure 4 shows the experimental setup of our buncher system together with the longitudinal potential diagram. The RFQ has a total length of 914 mm along the beam axis and a bore radius of $r_0 = 8.0\,\mathrm{mm}$. A resonant circuit technique is employed for the RF system. RF voltage of up to 500-V amplitude can be supplied with frequency range from 0.3 MHz to 3 MHz by tuning the resonant condition of the circuit. The ion source is surface ionization type and provides continuous alkali metal ion ($^{133}\mathrm{Cs}^{+}$, $^{39}\mathrm{K}^{+}$ or $^{23}\mathrm{Na}^{+}$) beam with accelerating voltage $V_{\mathrm{Acc}} = 6.0\,\mathrm{kV}$ constantly. The voltage V_{Barr} applied to the barrier electrode 1 and 2 is a few volts lower than V_{Acc} and higher than the DC voltage V_{DC} applied

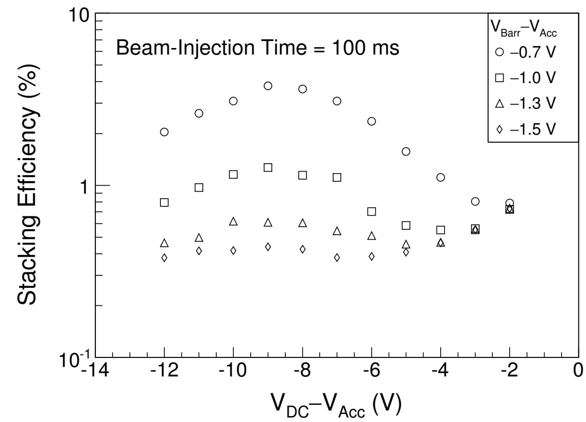

Figure 3: Ion stacking efficiency $\epsilon(t)$ of $^{133}\mathrm{Cs}^{+}$ plotted versus $V_{\mathrm{DC}} - V_{\mathrm{Acc}}$ for the beam injection time of $t = 100\,\mathrm{ms}$. V_{Acc}, V_{RF} and ω have same values as in Figure 1.

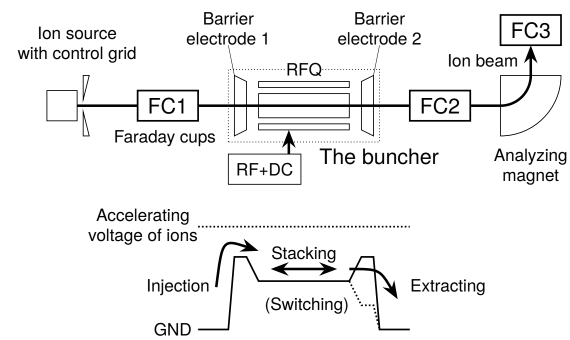

Figure 4: Experimental setup of the buncher system together with the longitudinal potential diagram.

to the RFQ rods for the injection of the ions into and stacking in the buncher. For the extraction of the stacked ions from the buncher the potential of the barrier electrode 2 is switched from V_{Barr} to $\approx V_{\mathrm{Acc}} - 100\,\mathrm{V}$ within less than ten microseconds by a fast transistor switch. The injected beam current I_{inj} and the total number of stacked ions (number of ions contained in the beam extracted from the buncher) $N(t)$ is measured by the Faraday cups named FC1-3.

MEASUREMENT OF THE ION STACKING EFFICIENCY

Figure 5 shows typical waveforms of the $^{23}\mathrm{Na}^{+}$ beam extracted from the buncher observed by FC2 for the beam-injection time of $t = 100\,\mathrm{ms}$, 500 ms and 900 ms. The ion beams extracted from the buncher with pulse width of about 500 µs which naturally depends on V_{DC} was obtained. In the case of $t = 100\,\mathrm{ms}$, as an example, the number of ions contained in the waveform is $N(t) \approx 1.0 \times 10^{8}$ and the injected beam current observed by FC1 is $I_{\mathrm{inj}} \approx 4.3\,\mathrm{nA}$. Therefore, the ion stacking efficiency including an injection and an extraction efficiency is

$$\epsilon(t) = N(t)\frac{e}{I_{\mathrm{inj}}t} = 3.8\,\% \tag{7}$$

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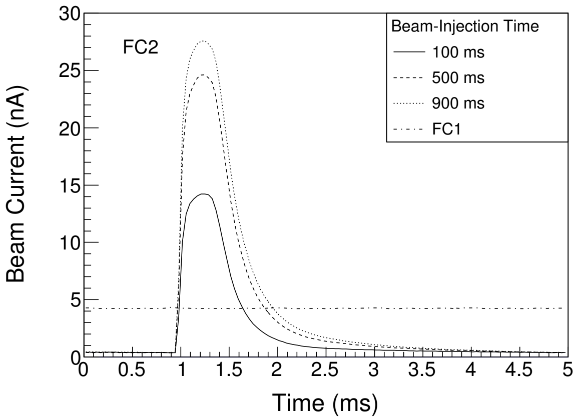

Figure 5: Typical waveforms of the $^{23}Na^{+}$ beam extracted from the buncher observed by FC2 for the beam-injection time of 100 ms, 500 ms and 900 ms where $V_{\rm Barr} = V_{\rm acc} - 1.3$ V, $V_{\rm DC} = V_{\rm acc} - 6.7$ V, $V_{\rm RF} = 150$ V and $\omega/2\pi = 1.9$ MHz. The dot-and-dash line shows the waveform of the injected beam observed by FC1.

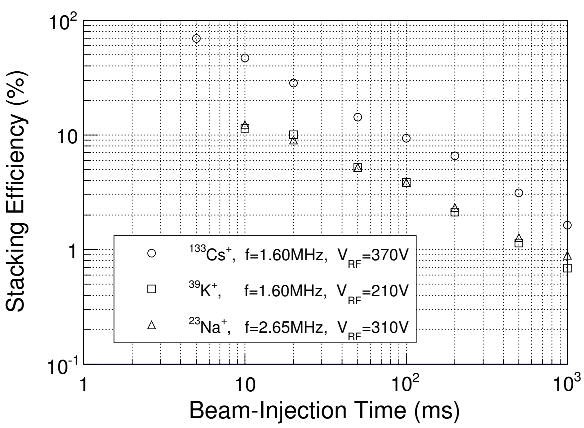

Figure 6: Experimental ion stacking efficiencys $\epsilon(t)$ of the $^{133}Cs^{+}$, $^{39}K^{+}$ and $^{23}Na^{+}$ beams. Values of $V_{\rm Barr}$, $V_{\rm DC}$, $V_{\rm RF}$ and ω have been optimized for each beam.

Such the experimental ion stacking efficiencys $\epsilon(t)$ of the $^{133}Cs^{+}$, $^{39}K^{+}$ and $^{23}Na^{+}$ beams are shown in Figure 6. Here, values of $V_{\rm Barr}$, $V_{\rm DC}$, $V_{\rm RF}$ and ω have been optimized for each beam, and it is known that ω have no effect on $\epsilon(t)$ essentially. Although the experimental result for the heavy $^{133}Cs^{+}$ beam reasonably reproduced the computational one shown in Figure 2, higher stacking efficiency of nearly 10 % was obtained for $t = 100$ ms or an operating frequency of the buncher of 10 Hz. Figure 7 shows dependency of the experimental $\epsilon(t)$ of $^{23}Na^{+}$ on $V_{\rm Barr}$ and $V_{\rm DC}$ for $t = 100$ ms where $V_{\rm RF} = 210$ V, and $\omega/2\pi = 1.9$ MHz. The computational result shown in Figure 3 was reproduced well. It is show that the ion stacking efficiency $\epsilon(t)$ heavily depend on $V_{\rm Barr}$ and $V_{\rm DC}$.

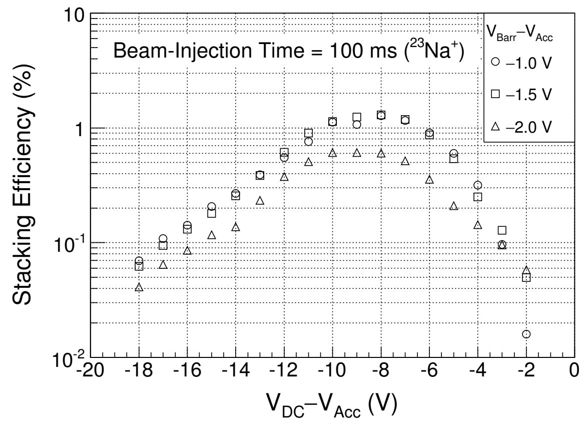

Figure 7: Dependency of the experimental ion stacking efficiencys $\epsilon(t)$ of $^{23}Na^{+}$ on $V_{\rm Barr}$ and $V_{\rm DC}$ for $t = 100$ ms where $V_{\rm RF} = 210$ V, and $\omega/2\pi = 1.9$ MHz.

CONCLUSIONS

The new-type buncher which is buffer gas-free and workable under the ultra-high vacuum for low energy RI ion beams was developed. Ion beams extracted from the buncher with pulse width of about 500 µs and the stacking efficiency of heavy ions such as $^{133}Cs^{+}$ of 10 % was obtained for the operating frequency of 10Hz. it has already been observed taht the efficiency is further enhanced by providing cooling force on the ions or by combination with pre-bunching at the ion source. The buncher system can be expected to be applied to various applications.

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